

# Measuring gravitational effects on antimatter in space

G.M. Piacentino<sup>a,b,c</sup>, A. Palladino<sup>d,e</sup>, G. Venanzoni<sup>d</sup>

<sup>a</sup>Università degli Studi del Molise, Campobasso, Italy

<sup>b</sup>INFN, Sezione di Lecce, Lecce, Italy

<sup>c</sup>INAF, Sezione di Milano, Milano, Italy

<sup>d</sup>Laboratori Nazionali di Frascati dell'INFN, Frascati, Italy

<sup>e</sup>Boston University, Boston, USA

---

## Abstract

We propose an experimental test of the gravitational interaction with antimatter by measuring the branching fraction of the CP violating decay  $K_L \rightarrow \pi^+\pi^-$  in space. We show that at the altitude of the International Space Station, gravitational effects may change the level of CP violation such that a  $5\sigma$  discrimination may be obtained by collecting the  $K_L$  produced by the cosmic proton flux within a few years.

**Keywords:** gravity, CP violation

**PACS:** 04.80.Cc, 11.30.Er, 14.40.Df

---

## 1. Introduction

The hypothesis that antimatter could have a different coupling to the gravitational field has fascinated physicists since the discovery of the first antiparticles. Various theoretical efforts have been put forth to demonstrate both the possibility of a different behavior or, on the contrary, the necessity of equal coupling. Several authors have shown that the possible gravitational repulsion between matter and antimatter could offer at least a partial explanation for a number of cosmological problems, including those connected to dark matter and dark energy [1–15].

At present, the state-of-the-art is not very different from the framework summarized in the article by Nieto et al. in 1991 [16]. Limits on repulsive gravity have been calculated based on measurements [17, 18]. A relatively large number of experiments on the gravitational interaction of antimatter have been proposed and even started, e.g. AEGIS [19], ALPHA [20], ATRAP [21], and GBAR [22]. In addition, the muonium experiment proposed at PSI [23, 24] is the first to involve a second generation fermion. Furthermore, aside from direct measurements in laboratories there are emerging astronomical tests as pointed out by [9, 10] and supported by a feasibility study [25] on a trans-Neptunian Binary System. Our proposal of measuring CP violation in a weaker gravitational field is complementary to both laboratory experiments and astronomical observations; it is simply a direct test of the dependence of CP violation on the gravitational field. Should such a dependence exist it would be a strong indication of particles and antiparticles having opposite coupling with gravity. Ultimately the only

measurements related to the topic at hand came from CPLEAR in 1999 [26] and proposed at KLOE in 2000 [27] where they looked for a modulation of CP violation due to gravitational tidal contributions from the Moon, the Sun, and the galaxy.

The experiment proposed in this article is based on Good's argument [28]. Good initially noted that the absence of CP violation in neutral kaon decays would experimentally rule out any possible gravitational repulsion between matter and antimatter. The discovery of CP violation has greatly limited the validity of Good's argument and various authors have considered variants of it both in favour and in opposition to the possible existence of a different gravitational coupling between matter and antimatter.

This topic deserves experimental tests and current investigations are ongoing in various laboratories on Earth. We instead propose to study a possible dependence of CP violation on the gravitational interaction in the  $K_S$ - $K_L$  system in space. The magnitude of any difference between the CP violation parameter,  $\varepsilon$ , measured in orbit and that measured on Earth's surface would give important indication on the nature of the gravitational interaction between matter and antimatter as well as provide evidence for a quantum gravitational effect. In this paper we outline a new approach to the problem capable of providing a  $5\sigma$  measurement.

## 2. Possible experimental setup

The mean gravitational field strength in a Low Earth Orbit (LEO) is about 10% less than on the Earth's surface. Following Chardin [1, 2] we consider a dependence of  $\varepsilon$  only on the local acceleration due to gravity,  $g$ , not on the gravitational potential. In circular orbits, such as a LEO,  $(g_{\text{orbit}} - g_{\text{surface}})/g_{\text{surface}}$  is stable and all external perturbations are at least an order-of-magnitude less and will not be considered in this paper. The

---

Email addresses: nanni@fnal.gov (G.M. Piacentino), palladin@bu.edu (A. Palladino), graziano.venanzoni@lnf.infn.it (G. Venanzoni)

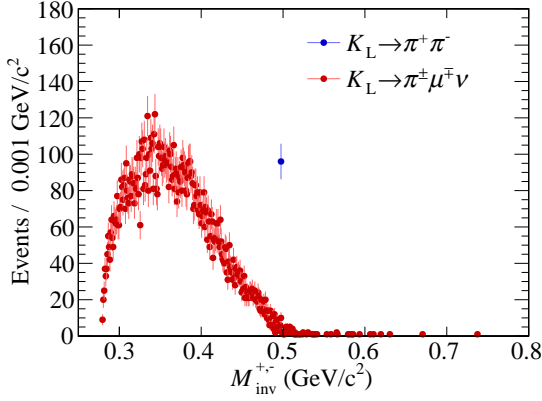


Figure 1: (Color online) Invariant mass calculated from the charged daughters of the  $K_L$  decays. For the 2-body decay we recover  $m_{K_L}$ . A fit to this distribution and other kinematical observables can easily provide knowledge of our background contributions with an uncertainty at the percent level,  $\delta B/S < 0.02$ .

rate of incoming protons in a LEO has been measured [29, 30], and when integrated on the permitted entrance to the detector can reach as many as  $2.2 \times 10^4$  protons per second. The energy of the cosmic protons ranges from a few MeV to  $\sim 200$  GeV with the maximum flux around 1 GeV and several smaller local maxima at 5, 13, and 31 GeV.

The incident proton spectrum is energetic enough for the production of  $K_L$  allowing for a measurement of

$$R = \frac{\Gamma(K_L \rightarrow \pi^+ \pi^-)}{\Gamma(K_L \rightarrow \pi^+ \pi^- \pi^0)} \quad (1)$$

which is quadratic in  $\varepsilon$ . If CP violation depends linearly on the gravitational field [1, 2] we expect a 10% effect in  $\varepsilon$  to translate to a 20% effect on  $R$ .

To make a  $5\sigma$  measurement of a 20% effect on  $R$  we would need to record at least  $12.5 \times 10^5$   $K_L$  decays, with  $N(K_S \text{ decays})/N(K_L \text{ decays}) < 5.7 \times 10^{-5}$ , while keeping the uncertainty in the background at less than 0.02 of our signal,  $\delta B/S < 2\%$ . The background contribution from  $K_L \rightarrow \pi^\pm \mu^\mp \nu$  can be easily obtained with an uncertainty at the percent level by fits to kinematical observables such as the invariant mass calculated from the two charged tracks (Figure 1). The corresponding values necessary for a  $3\sigma$  measurement are listed in Table 1. As we will see in the following section this yield can be achieved on the proposed LEO within a few years of data taking.

### 3. Simulation

We performed a GEANT4 [31, 32] Monte Carlo simulation using the angular and energy spectrum of the incident cosmic protons as measured by AMS-01 spectrometer. We simulated incident protons with  $\theta_{\max} = 45^\circ$  over a 50 cm radius target surface corresponding to a  $\pi/4$  solid-angle acceptance.

Figure 2 shows results from an optimization study of target material and depth. Even though more  $K_L$  are produced for

thicker targets, the probability that they exit the thicker targets is reduced due to regeneration and nuclear interactions.

The detector geometry consists of a target composed of layers of tungsten and thin planes of active detectors with the tungsten having a cumulative depth of 9 cm and a radius of 50 cm. Downstream of the target is a  $\sim 50$  cm deep charged-particle detector such as the Transition Radiation Detector (TRD) in AMS-02. Next comes a cylindrical tracking volume followed at the downstream end by electromagnetic calorimeter. The tracking region would be surrounded by a veto system to identify cosmic rays entering from the side. The active layers sandwiched in the target would identify the parent incident proton and record the time and position of the interaction point. Charged-particle backgrounds produced in the target would be identified in the charged-particle detector between the target and the tracking region. The neutral  $K_{S,L}$  produced in the target, would travel into the cylindrical tracking region where they then decay. Data analysis will select  $K_L \rightarrow \pi^+ \pi^-$  and  $K_L \rightarrow \pi^+ \pi^- \pi^0$  events with interaction vertices inside the tracking region which has a  $> 50$  cm displacement with respect to the target thereby significantly reducing background contamination. We found that the axial momentum ( $p_z$ ) distributions, Figure 3, for the  $K_L$  and  $K_S$  in the tracker differ such that we can suppress the  $K_S \rightarrow \pi^+ \pi^-$  background with the cut  $p_z < 0.5$  GeV/c. Figure 4 shows the effect of the momentum cut. Considering a cylindrical tracking region with 1 m diameter, 1 m deep, and offset 0.5 m downstream of the target, we would obtain the results given in Table 1.

Table 1: Critical parameters necessary for  $3\sigma$  and  $5\sigma$  measurements of a 10% change in the level of CP violation (20% change in  $R$ ) along with the values obtained from our Monte Carlo simulation. The results take into account a basic geometrical event selection of  $K_{S,L}$  decay vertices within a  $1 \text{ m} \times 1 \text{ m}$  cylindrical tracking volume 50 cm downstream of the target ( $50 < z < 150$  cm,  $r < 50$  cm), and axial momentum at the  $K_{S,L}$  decay vertex of  $p_z < 0.5$  GeV/c. These values assume a 100% detection efficiency, 2% (4%) statistical and 2% (4%) systematic fractional uncertainties for  $5\sigma$  ( $3\sigma$ ).

	Requirement		Simulation result	
	$3\sigma$	$5\sigma$	$3\sigma$	$5\sigma$
$N(K_L \text{ decays})$	$> 3 \times 10^5$	$> 12.5 \times 10^5$	73 days	304 days
$\frac{N(K_S \text{ decays})}{N(K_L \text{ decays})}$	$< 1 \times 10^{-4}$	$< 5.7 \times 10^{-5}$	$4.1 \times 10^{-5}$	
$\frac{\delta N(K_L \rightarrow \pi \mu \nu)}{N(K_L \rightarrow \pi \pi)}$	$< 4 \times 10^{-2}$	$< 2 \times 10^{-2}$	kinematical cuts	

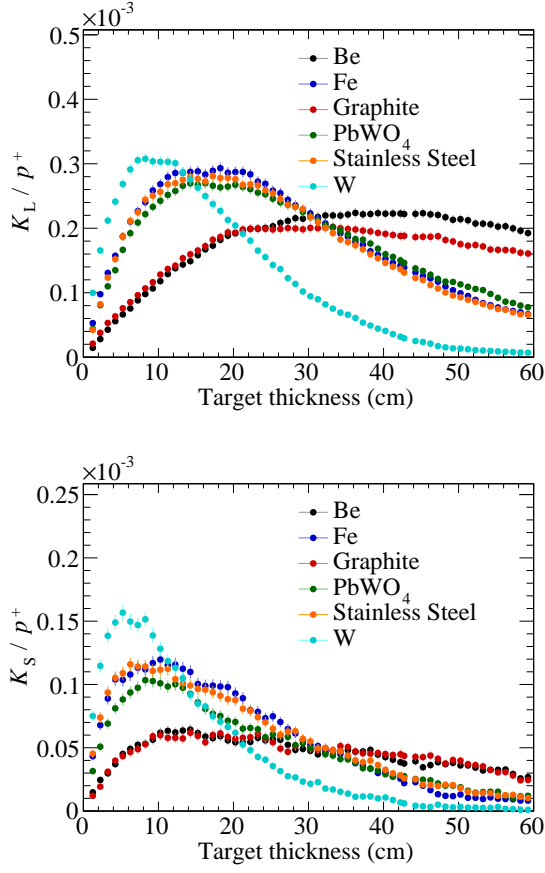


Figure 2: (Color online) Number of  $K_L$  (top) and  $K_S$  (bottom) which exit the downstream face of the target versus target thickness for several materials. For our subsequent studies we used a 9 cm tungsten target which produced the most  $K_L$  with the shortest target thickness.

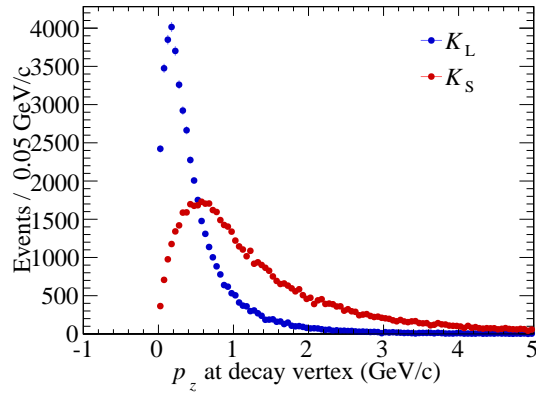


Figure 3: (Color online) Axial momentum of the  $K_{S,L}$  at their decay vertex, for the  $K_{S,L}$  which decay in the tracking region downstream of the target,  $z > 0$ .

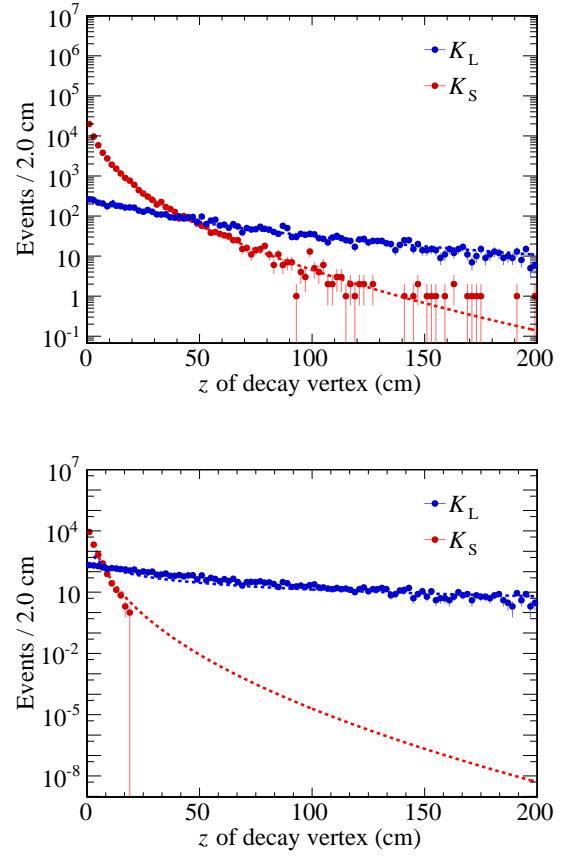


Figure 4: (Color online) Axial position of the  $K_{S,L}$  decay vertex for  $r < 50$  cm (top) and with the additional constraint  $p_z < 0.5$  GeV/c (bottom).

## Conclusions

We have proposed a possible test of the gravitational behavior of antimatter by measuring the rate of the CP violating decay  $K_L \rightarrow \pi^+ \pi^-$  in space. We estimate that a  $5\sigma$  measurement on a possible change in the CP violation parameter  $\varepsilon$  could be obtained within a year, depending on the detection efficiency, if one places a detector with a 9 cm thick tungsten target, a 1 m diameter by 1 m deep tracking region, a magnetic field for charged-particle identification, time-of-flight counters, and electromagnetic calorimeters for energy measurements, on the International Space Station. Any difference between the amount of CP violation in orbit with respect to the level CP violation on the Earth's surface would be an indication of the nature of the gravitational interaction between matter and antimatter. A positive result may offer an explanation for the cosmic baryon asymmetry and may offer a contribution to the observed effects thought to come from dark matter and dark energy [1–15]. A negative result would also be of interest, confirming that the level of CP violation is independent of the absolute gravitational field. Finally, we note that even if a target system is absent in existing satellite experiments such as AMS-02 [33] and Pamela [34], it is possible that a number of  $K_L$  events have been recorded during data taking and are still available for analysis allowing for a first glance of the phenomenon.

## 4. Acknowledgements

We thank G. Chardin, D.S. Hajdukovic, G. Lamanna, E. Recami, and G.F. Bignami for useful discussions and suggestions.

## 5. References

- [1] G. Chardin, CP violation and antigravity (revisited), *Nucl. Phys. A* 558 (1993) 477c.
- [2] G. Chardin, J. M. Rax, CP violation. A matter of (anti)gravity?, *Phys. Lett. B* 282 (1992) 256–262.
- [3] A. Benoit-Lévy and G. Chardin, Introducing the Dirac-Milne universe, *Astron. Astrophys.* 537 (A78).
- [4] A. Benoit-Lévy and G. Chardin, The Dirac-Milne cosmology, *International Journal of Modern Physics: Conference Series. Antimatter and Gravity Conference (WAG 2013)* 30 (2014) 1460272.
- [5] D.S. Hajdukovic, Is dark matter an illusion created by the gravitational polarization of the quantum vacuum?, *Astrophysics and Space Science* 334 (2011) 215–218.
- [6] D.S. Hajdukovic, Do we live in the universe successively dominated by matter and antimatter?, *Astrophysics and Space Science* 334 (2011) 219–223.
- [7] D.S. Hajdukovic, Quantum vacuum and dark matter, *Astrophysics and Space Science* 337 (2012) 9–14.
- [8] D.S. Hajdukovic, Quantum vacuum and virtual gravitational dipoles: the solution to the dark energy problem?, *Astrophysics and Space Science* 339 (2012) 1–5.
- [9] D.S. Hajdukovic, Virtual gravitational dipoles: The key for the understanding of the universe?, *Physics of the Dark Universe* 3 (2014) 34–40.
- [10] D.S. Hajdukovic, What if quantum vacuum fluctuations are virtual gravitational dipoles?, *Proceedings of the 3rd International Workshop on Antimatter and Gravity (WAG 2015)*.  
URL <https://hal.archives-ouvertes.fr/hal-01254678v2>
- [11] M. Villata, On the nature of dark energy: the lattice Universe, *Astrophysics and Space Science* 345 (2013) 1–9.
- [12] L. Blanchet, Gravitational polarization and the phenomenology of MOND, *Class. Quant. Grav.* 24 (2007) 3529.
- [13] L. Blanchet and A. Le Tiec, Model of Dark Matter and Dark Energy Based on Gravitational Polarization, *Phys. Rev. D* 78 (2008) 024031.
- [14] L. Blanchet and A. Le Tiec, Dipolar Dark Matter and Dark Energy, *Phys. Rev. D* 80 (2009) 023524.
- [15] L. Bernard and L. Blanchet, Phenomenology of Dark Matter via a Bimetric Extension of General Relativity, *Phys. Rev. D* 91 (2015) 103536.
- [16] M. M. Nieto and T. Goldman, The arguments against “antigravity” and the gravitational acceleration of antimatter, *Physics Reports* 205 (1991) 221–281.
- [17] D.S.M. Alves, M. Jankowiak, P. Saraswat, Experimental constraints on the free fall acceleration of antimatter.  
URL [arXiv:0907.4110v1](https://arxiv.org/abs/0907.4110v1)
- [18] M. Fischler, J. Lykken, T. Roberts, Direct observation limits on antimatter gravitation.  
URL [arXiv:0808.3929v1](https://arxiv.org/abs/0808.3929v1)
- [19] A. Kellerbauer et al. (AEGIS Collaboration), Proposed antimatter gravity measurement with an antihydrogen beam, *Nuclear Instrum. and Methods in Phys. Research B* 266 (2008) 351. doi:10.1016/j.nimb.2007.12.010.
- [20] A.E. Charman et al. (ALPHA Collaboration), Description and first application of a new technique to measure the gravitational mass of antihydrogen, *Nature Comm.* 4 (2013) 1785.
- [21] G. Gabrielse et al. (ATRAP Collaboration), Trapped antihydrogen in its ground state, *Phys. Rev. Lett.* 108 (2012) 113002.
- [22] G. Chardin, P. Grandemange, D. Lunney, et al., Proposal to measure the gravitational behaviour of antihydrogen at rest, *Tech. Rep. CERN-SPSC-2011-029*, SPSC-P-342.
- [23] K. Kirsch, Testing Gravity with Muonium.  
URL [arXiv:physics/0702143](https://arxiv.org/abs/physics/0702143)
- [24] D.M. Kaplan et al., Measuring Antimatter Gravity with Muonium.  
URL [arXiv:1308.0878](https://arxiv.org/abs/1308.0878)
- [25] M. Gai and A. Vecchiato, Astrometric detection feasibility of gravitational effects of quantum vacuum.  
URL [arXiv:1406.3611](https://arxiv.org/abs/1406.3611)
- [26] CPLEAR Collaboration, Tests of the Equivalence Principle with Neutral Kaons, *Phys. Lett. B* 452 (1999) 425–433, CERN-EP/99-22.  
URL [arXiv:hep-ex/9903005](https://arxiv.org/abs/hep-ex/9903005)
- [27] G. Mambriani, L. Trentadue, Testing CP Conservation at KLOE.  
URL [arXiv:hep-ex/0007004](https://arxiv.org/abs/hep-ex/0007004)
- [28] M. L. Good,  $K_2^0$  and the Equivalence Principle, *Phys. Rev.* 121 (1961) 311–313.
- [29] AMS Collaboration, Protons in near earth orbit, *Phys. Lett. B* 427 (2000) 251–226.
- [30] AMS Collaboration, Cosmic protons, *Phys. Lett. B* 490 (2000) 27–35.
- [31] S. Agostinelli, et al., Geant4: A simulation toolkit, *Nucl. Instrum. Meth. A* 506 (2003) 250–303.
- [32] Geant4 developments and applications, *IEEE Transactions on Nuclear Science* 53 (2006).
- [33] AMS-02 Collaboration, First Result from the Alpha Magnetic Spectrometer on the International Space Station: Precision Measurement of the Positron Fraction in Primary Cosmic Rays of 0.5350 GeV, *Phys. Rev. Lett.* 110 (2013) 141102.
- [34] Pamela Collaboration, A payload for antimatter matter exploration and light-nuclei astrophysics, *Astropart. Phys.* 27 (2007) 296–315.